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RESEARCH MEMORANDUM

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HEPTANE-OXYGEN ROCKET ENGINES

By Richard J. Priem and Martin Hersch

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RESEARCH MEMORANDUM

EFFECT OF FUEL-ORIFICE DIAMETER ON PERFORMANCE

OF HEPTANE-OXYGEN ROCKET ENGINES

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SUMMARY

The effect of fuel-orifice diameter on the performance of heptane-oxygen rocket engines with single-element injectors was studied. Five engines ranging from 50 to 800 pounds thrust were tested with parallel-sheet, triplet, and parallel-jet injectors. Characteristic exhaust velocity was determined for chamber lengths of 1 to 16 inches and for a narrow range of mixture ratios.

Decreasing the fuel-orifice diameter increased the performance for a fixed chamber length. The chamber length required to obtain the same engine performance varied with the second power of fuel-orifice diameter for a parallel-sheet injector and with the 3/2 power of fuel-orifice diameter for a triplet injector.

Experimental performance results agree with analytical results based on propellant vaporization as the rate-controlling combustion process if the mass-median drop size is assumed proportional to the 1.4 power of the orifice diameter for a parallel-sheet injector, and to the first power for a triplet injector. The experimental results also agree with the calculations for a spray if the geometric standard deviation for mass distribution is assumed to be 3.5 for the parallel-sheet injector and 20 for the triplet injector.

INTRODUCTION

The development of large-thrust liquid-propellant rocket engines is usually extremely costly and time-consuming because of the trial-and-error process used. This development technique has been dictated by the lack of experimental information on the effects of different design parameters and the lack of similarity relations. A recent analytical investigation (ref. 1) to determine the propellant vaporization rates in rocket engines indicates that vaporization may be the rate-controlling combustion process in rocket engines. This greatly simplifies the

problem of rocket engine scaling as presented in references 2, 3, and 4, where the mixing, chemical-reaction, and diffusion processes are also considered. With the simplified model of vaporization as the rate-controlling combustion process, it was shown that propellant drop size, which can vary over a wide range, would give the largest effect on engine performance. One technique for achieving different drop sizes is to change the diameter of the orifice through which the propellants are injected (refs. 5 and 6).

The investigation reported herein was therefore conducted to provide experimental data on the fuel-orifice diameter required to obtain a given engine performance and to verify experimentally the calculated effect of changes in drop size.

APPARATUS AND PROCEDURE

Rocket Engines

The engines (fig. 1) were designed for a nominal chamber pressure of 300 pounds per square inch. The nominal thrusts used in the investigation were 50, 100, 200, 400, and 800 pounds. The chamber lengths varied from 1 to 16 inches. The injector, uncooled chamber, and uncooled nozzle were separate units. Spark ignition was used for engine starting. The contraction ratio of the engine was 2.5 for the parallel-sheet injectors. The heat transfer with this contraction ratio was quite high and the engines frequently burned out. The contraction ratio was therefore increased to 5.0 for the triplet and parallel-jet injectors.

Injectors

The design details of the three types of injectors are shown in figure 2. The injectors have the same design as those used in reference 7. The injectors were dimensionally scaled to keep injection velocity and the ratio of orifice spacing to orifice diameter constant.

Performance Measurements

Engine performance was evaluated in terms of the characteristic exhaust velocity c^*. Flow rates were measured by rotating-vane flowmeters that had a maximum error of ±2 percent. Reproducibility of flowmeter readings was generally within ±1 percent. The liquid oxygen was maintained at constant temperature in a liquid-nitrogen bath. Chamber pressure was measured with a direct-recording Bourdon instrument that had a maximum error of ±2 percent. Reproducibility of pressure readings was generally within ±1 percent. Nozzle-throat area measurements were

reproducible within ±1 percent. The accuracy of c^* data with these instruments was therefore ±5 percent. Reproducibility of c^* measurements for a particular engine and set of instruments was generally within ±2 percent.

The c^* measurements are reported as a percentage of the theoretical performance at the operating mixture ratio (c^* efficiency). Theoretical equilibrium composition and performance for heptane and oxygen at a chamber pressure of 300 pounds per square inch absolute are shown in figure 3.

Test Procedure

The characteristic exhaust velocity c^* was determined for oxidant-fuel weight ratios between 2.2 and 3.0. Test firings were of about 3-second duration. The total flow rates were approximately 0.225, 0.45, 0.9, 1.8, and 3.6 pounds per second for the 50-, 100-, 200-, 400-, and 800-pound thrust engines, respectively.

RESULTS AND DISCUSSION

Injector Performance

The c^* efficiency as a function of chamber length is shown in figures 4(a) and (b) for the parallel-sheet and triplet injectors, respectively. Each point represents the arithmetic average of five or more runs. The c^* efficiency for a given engine thrust increases with chamber length. For a given chamber length the c^* efficiency increases with a decrease in fuel-orifice diameter or decrease in engine thrust for both types of injectors, as shown in figures 5(a) and (b). The solid lines in figures 4 and 5 are believed to fit the data best.

The performance of the parallel-jet injector was low and the engine was very rough, making it difficult to obtain accurate c^* measurements. However, the parallel-jet injector showed the same tendencies as the triplet and the parallel-sheet injectors: performance increased with chamber length for a fixed fuel-orifice diameter and increased with decreasing fuel-orifice diameter or engine thrust for a fixed chamber length. The averaged results of 20 runs with the parallel-jet injector are shown in the following table:

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Thrust, lb	Chamber length, in.	Average c* efficiency, percent of theoretical
50	6	57
100	4	48
100	8	50
400	8	32

The chamber lengths required for a given c^* efficiency for various orifice diameters are shown in figure 6 for the parallel-sheet and the triplet injectors. The solid lines are crossplots of the curves drawn through the data points in figure 4. The slope of the lines is 2.0 for the parallel-sheet injector and 1.5 for the triplet. This means that the chamber length required to obtain the same engine performance varies with the second power of the fuel-orifice diameter for the parallel-sheet injector, and with the 3/2 power of the orifice diameter for a triplet injector.

Comparison of Experimental and Analytical Results

The results obtained in this investigation are compared in figure 7 with the calculated results reported in reference 8. Since the mass-median drop size and the geometric standard deviation of the sprays were unknown, the comparison was made by extrapolating the experimental data to a c^* efficiency of 58 percent, which is shown in reference 8 to be a common point for all deviations. The geometric standard deviation σ_g is a measure of the mass distribution of drop size and is defined in reference 8. With the extrapolated chamber length for 58-percent c^* efficiency, the effective-length term given in reference 8 was solved to determine the mass-median drop radius $M_{g,M}$. The indicated mass-median drop sizes were dependent on the fuel-orifice diameter D as follows:

Parallel-sheet injector,

$$M_{g,M} = 0.11\ D^{1.4}$$

Triplet injector,

$$M_{g,M} = 4.5 \times 10^{-3}\ D$$

The c^* efficiency and the percent mass vaporized as functions of effective length as shown in figure 7 indicate that the experimental results agree with the calculated results for a spray having a geometric

standard deviation σ_g of approximately 3.5 for the parallel-sheet injector. For the triplet injector the standard deviation was estimated as 20 from figure 9 of reference 8. The triplet injector evidently produces finer atomization, inasmuch as the mass-median radius is lower than for the parallel-sheet injector, as shown in figure 8. However, the triplet injector must also have a large number of the large drop sizes to produce a large standard deviation.

SUMMARY OF RESULTS

An investigation of the effect of fuel-orifice diameter on rocket-engine performance has shown that:

1. Decreasing the fuel-orifice diameter increases performance for a fixed engine length.

2. The chamber length required to maintain a given engine performance varies with the second power of the fuel-orifice diameter for the parallel-sheet injector and with the 3/2 power of the orifice diameter for a triplet injector.

3. The parallel-jet injector indicated the same trends as the parallel-sheet and the triplet injectors.

Comparison of the experimental results with analytical studies based on propellant vaporization as the rate-controlling process has shown that the experimental results agree with the analytical results if:

1. Mass-median drop size is assumed proportional to the 1.4 power of the fuel-orifice diameter for a parallel-sheet injector and to the first power for a triplet injector.

2. The geometric standard deviation is assumed to be 3.5 for the parallel-sheet injector and 20 for the triplet injector.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, October 14, 1957

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   tions of Heptane Drops. NACA TN 4098, 1957.

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Figure 1. - Rocket engines.
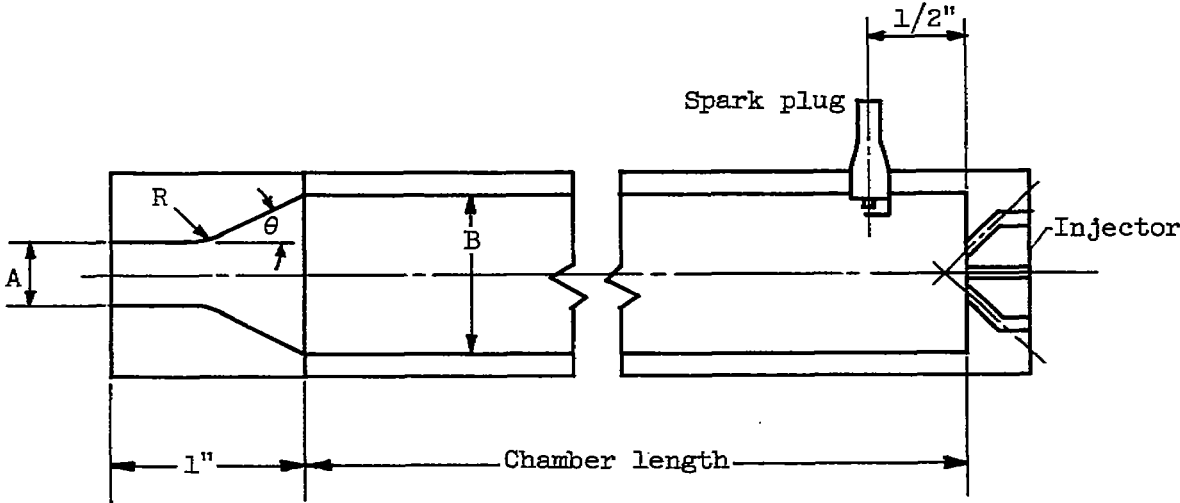
Thrust, lb	Triplet and parallel-jet injectors				Parallel-sheet injector			
	A, in.	B, in.	R, in.	θ, deg	A, in.	B, in.	R, in.	θ, deg
50	0.396	0.865	0.25	30	0.396	0.610	0.25	60
100	.557	1.240	.38	30	.557	.865	.38	60
200	.791	1.740	.50	45	.791	1.240	.50	60
400	1.120	2.485	.75	45	1.120	1.740	.75	60
800	1.581	3.500	1.00	45	1.581	2.485	1.00	60
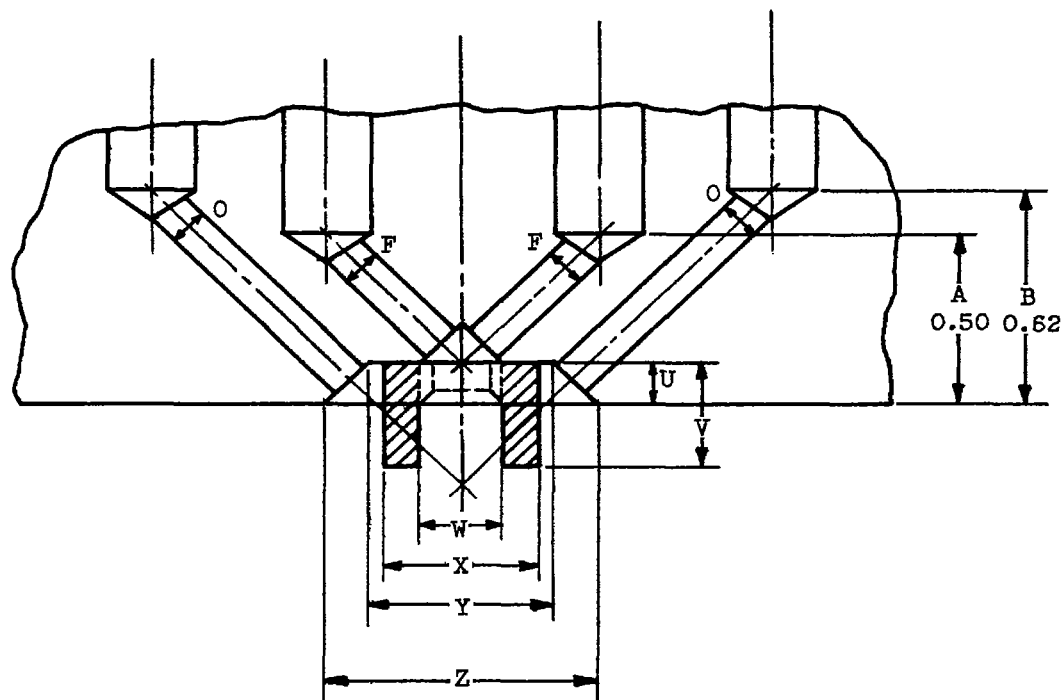
Thrust, lb	F	O	U	V	W	X	Y	Z
50	0.0430	0.0550	0.065	0.155	0.125	0.250	0.265	0.375
100	.0595	.0785	.085	.215	.175	.355	.370	.535
200	.0860	.1110	.125	.315	.245	.500	.515	.745
400	.1160	.1570	.175	.435	.345	.705	.720	1.065
800	.1660	.2210	.245	.625	.495	1.000	1.015	1.500

(a) Parallel sheets.

Figure 2. - Injectors. (All dimensions in inches.)

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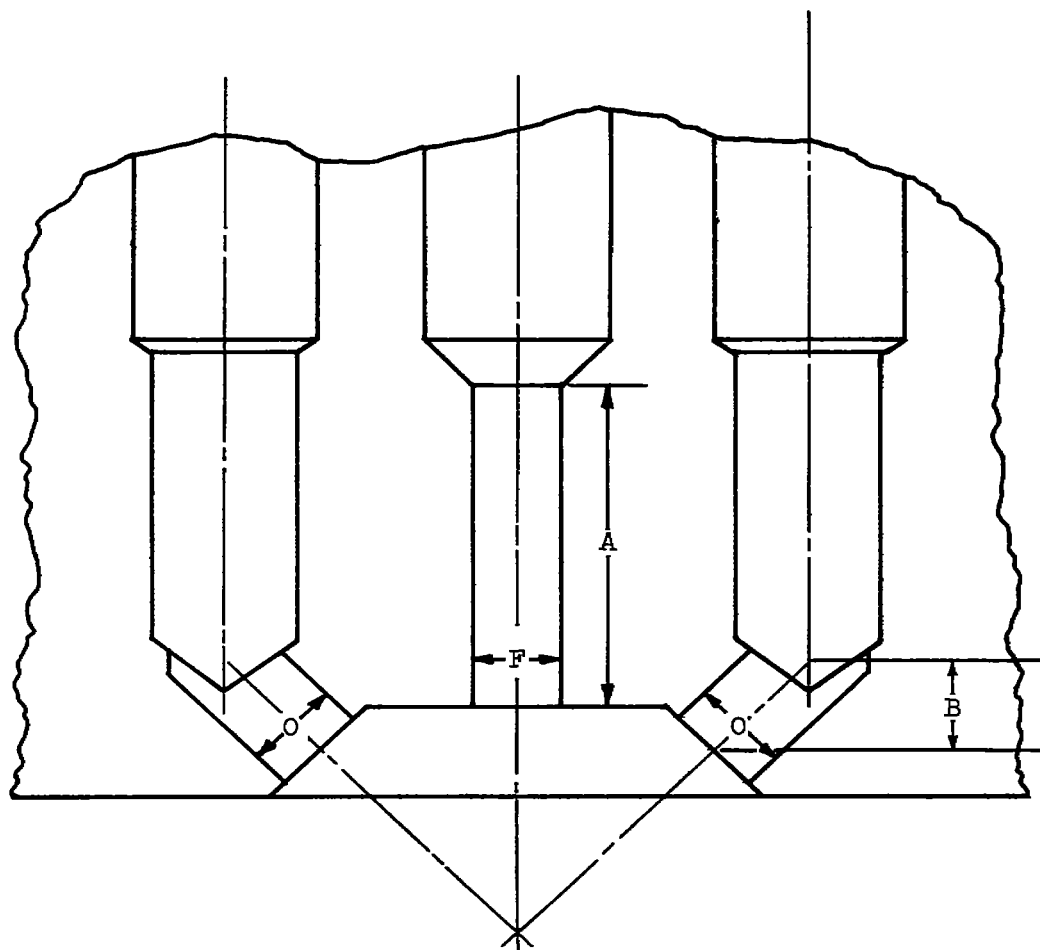
Thrust, lb	F	O	A	B
50	0.0595	0.0550	0.87	0.1025
100	.0820	.0785	.85	.1165
200	.1160	.1110	.81	.201
400	.1660	.1570	.76	.406
800	.2340	.2210	.69	.562

(b) Triplet.

Figure 2. - Continued.   Injectors.   (All dimensions in inches.)
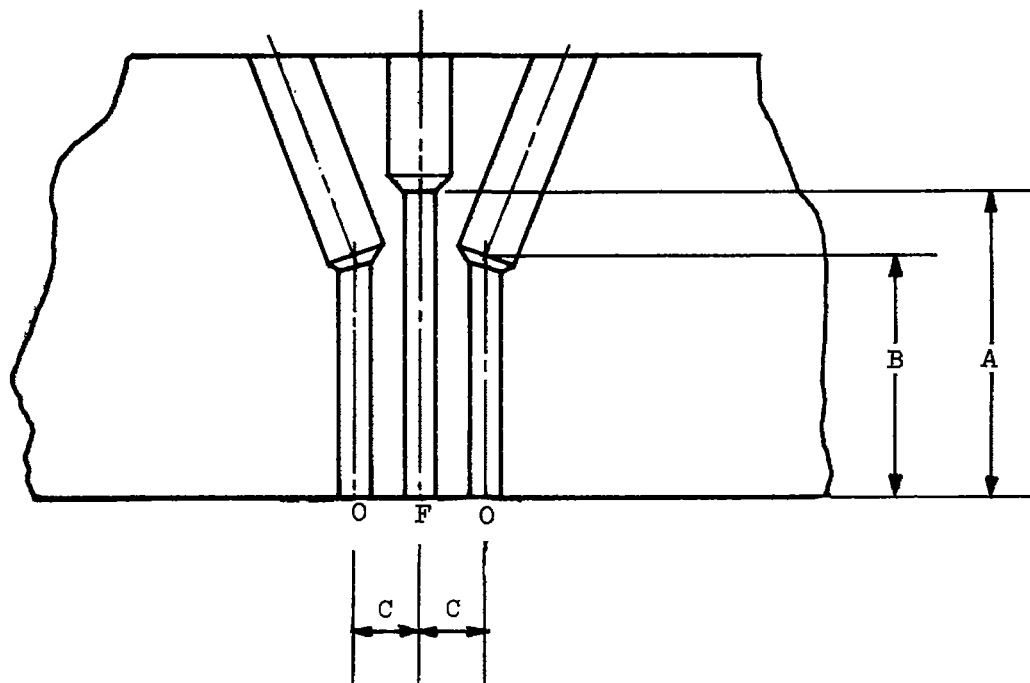
Thrust, lb	F	Q	A	B	C
50	0.0595	0.0550	0.625	1.226	0.125
100	.0820	.0785	.625	1.170	.175
200	.1160	.1110	1.312	1.002	.250
400	.1660	.1570	1.312	.960	.350
800	.2340	.2210	1.312	.945	.500

(c) Parallel jets.

Figure 2. - Concluded. Injectors. (All dimensions in inches.)

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Figure 3. - Theoretical equilibrium combustion properties of heptane-oxygen propellant combination at chamber pressure of 300 pounds per square inch absolute.
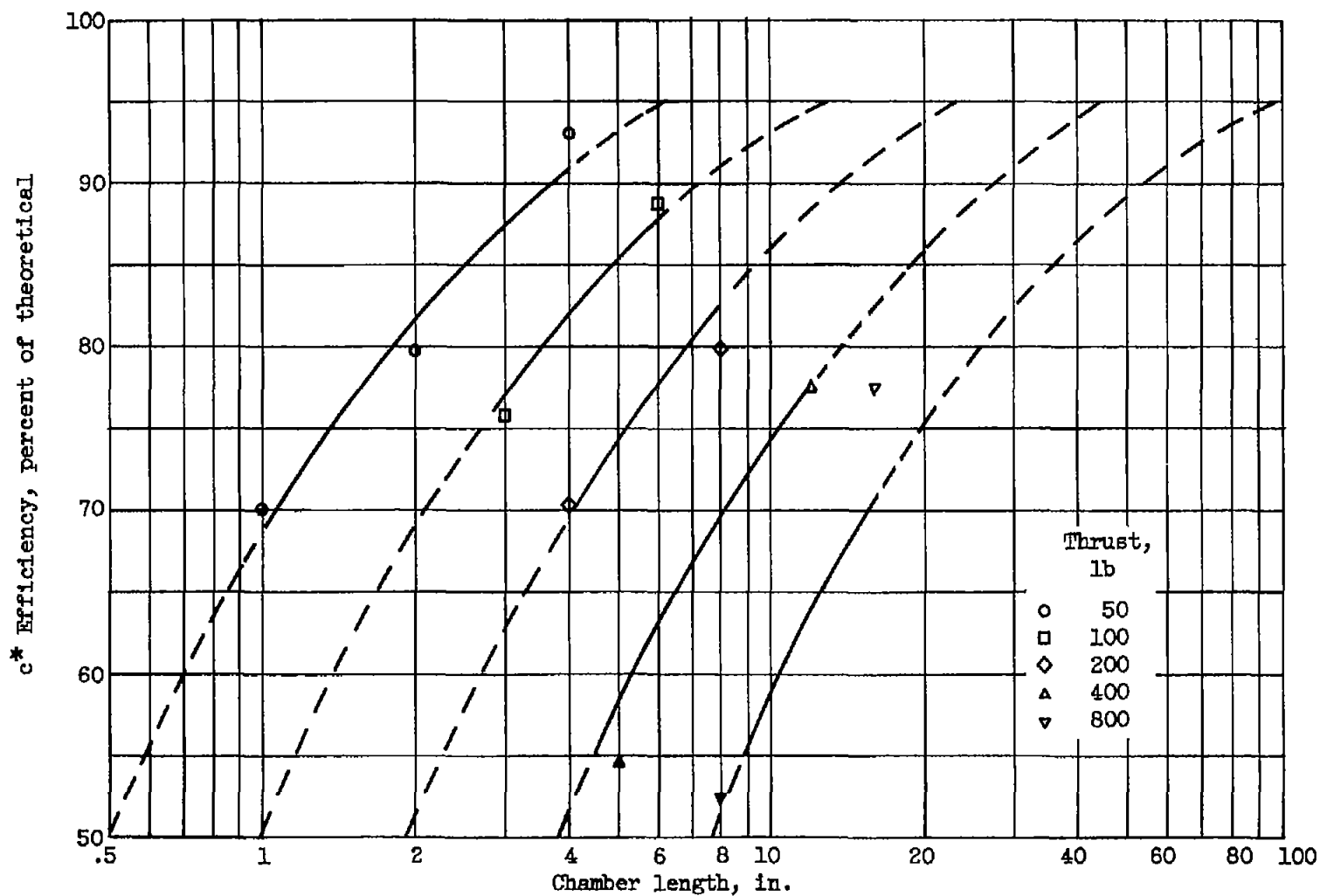
(a) Parallel-sheet injector.

Figure 4. - Effect of chamber length on performance.
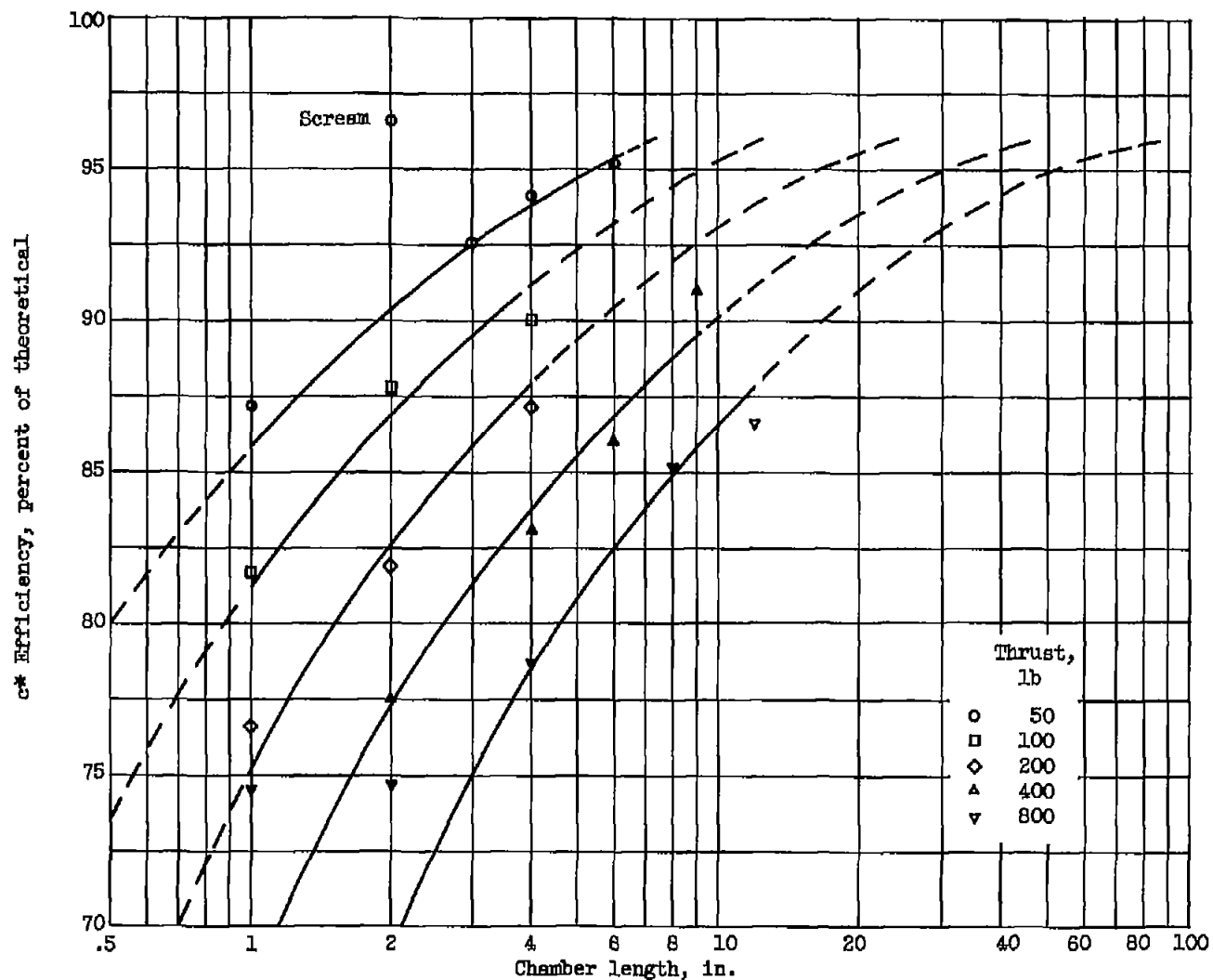
(b) Triplet injector.

Figure 4. - Concluded. Effect of chamber length on performance.
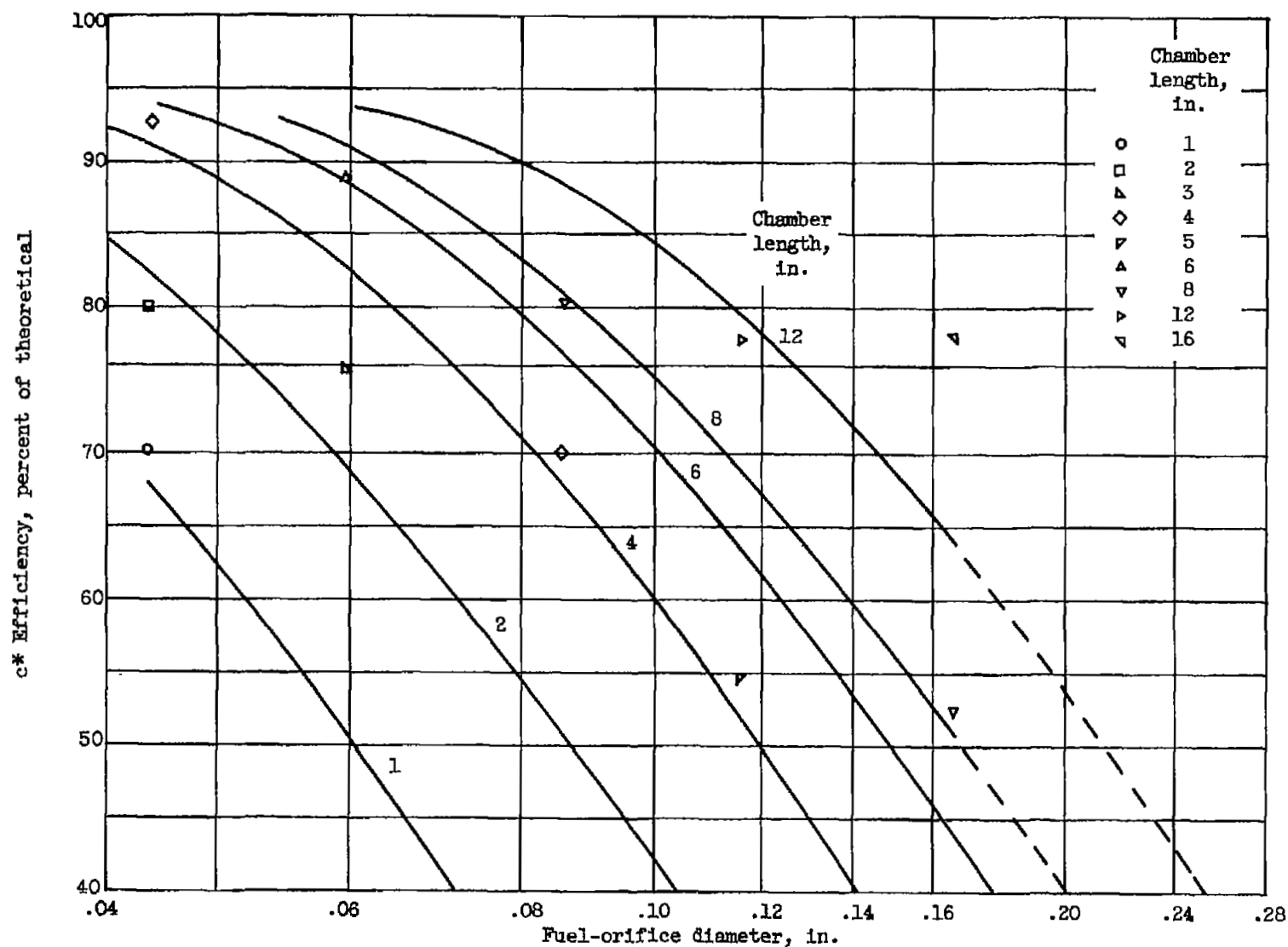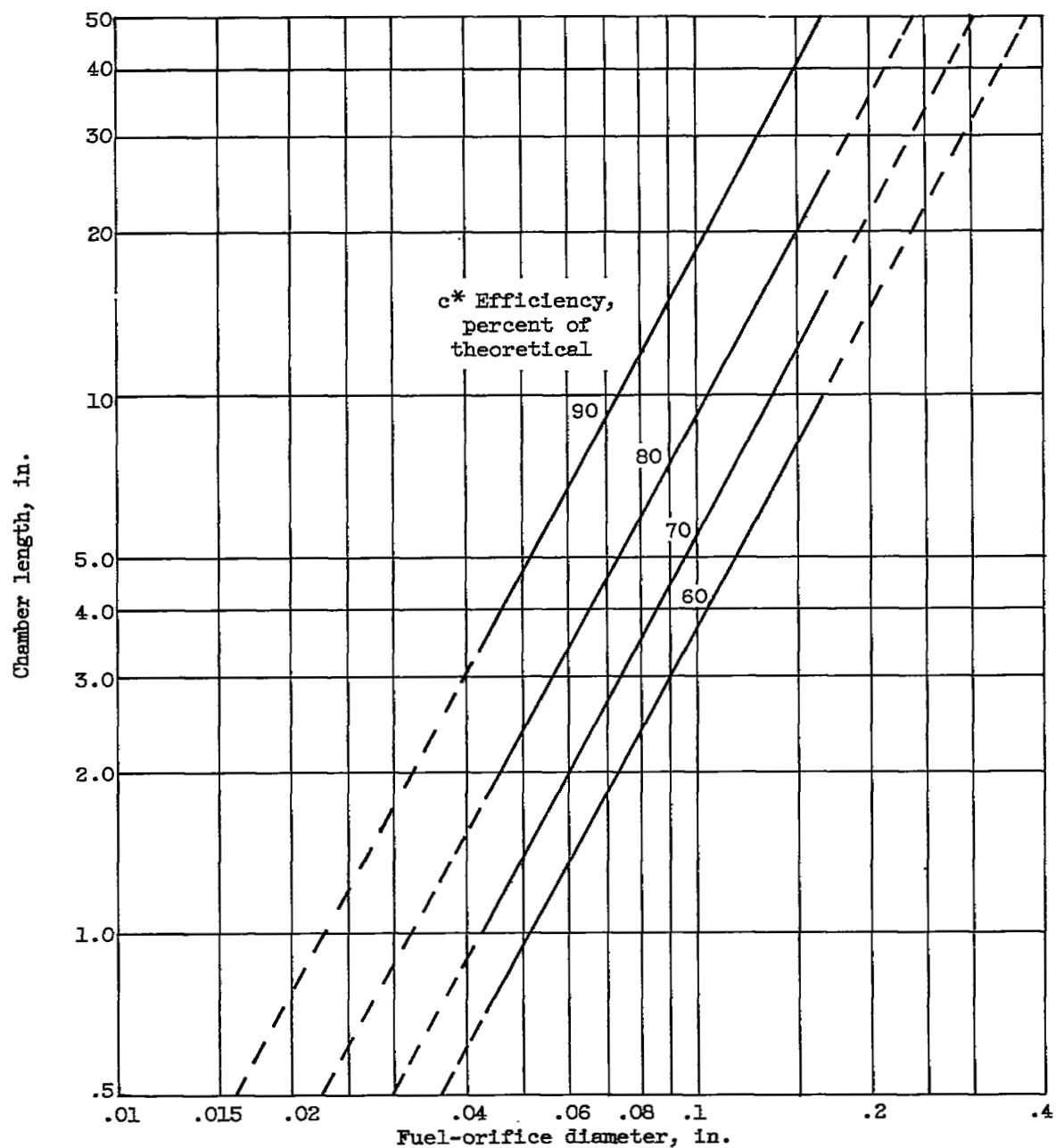
(a) Parallel-sheet injector.

Figure 5. - Effect of fuel-orifice diameter on performance.
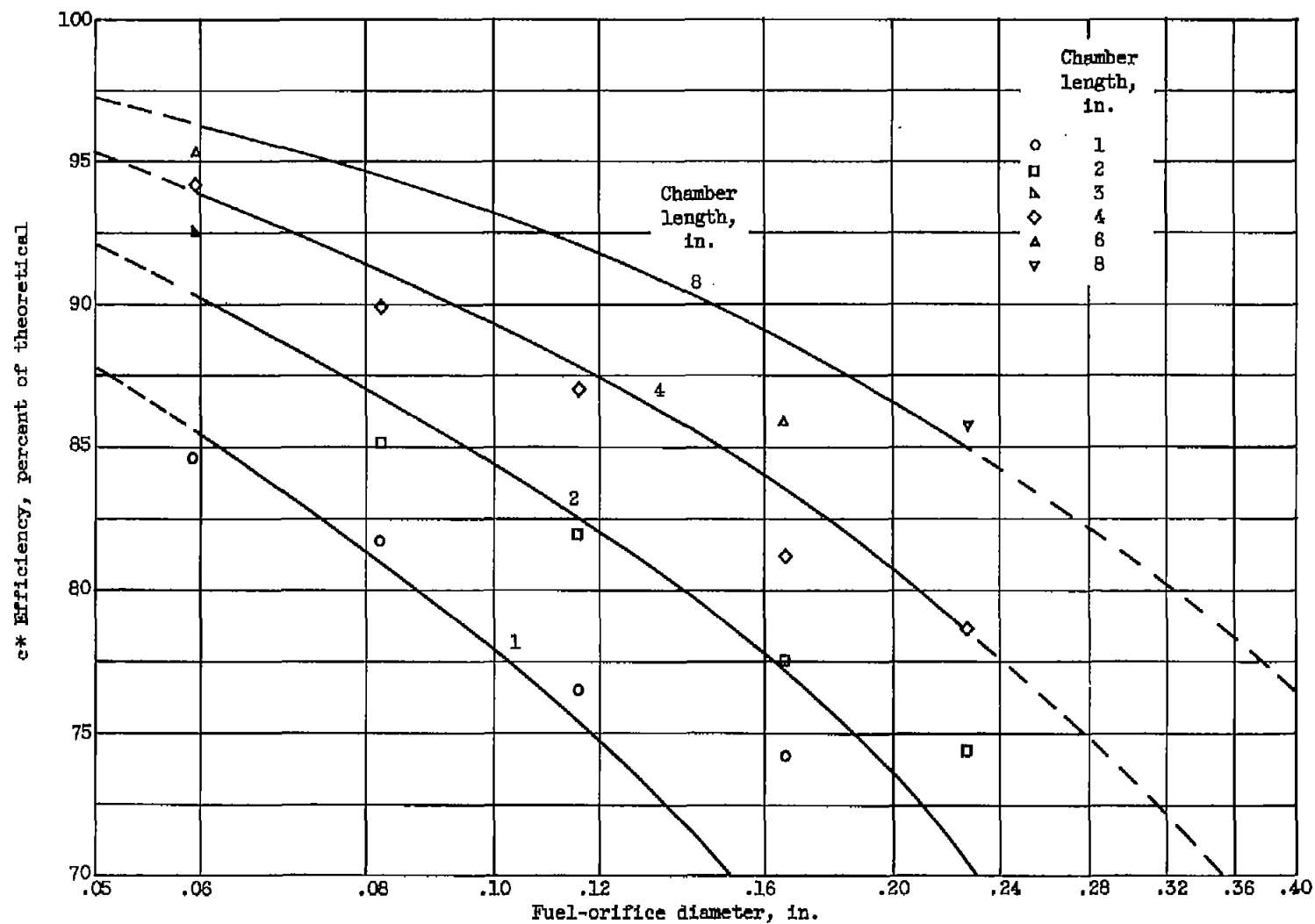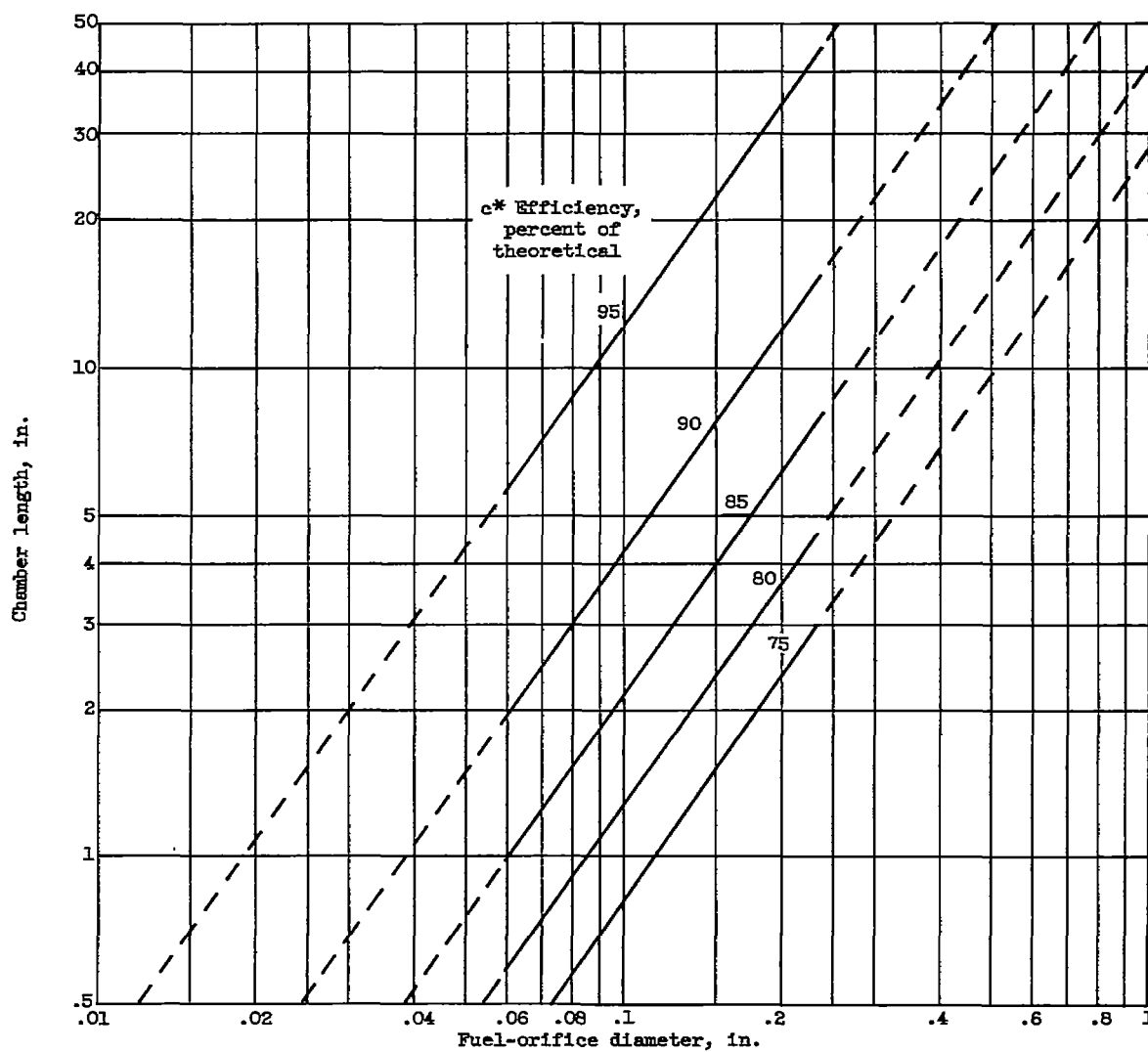
(b) Triplet injector.

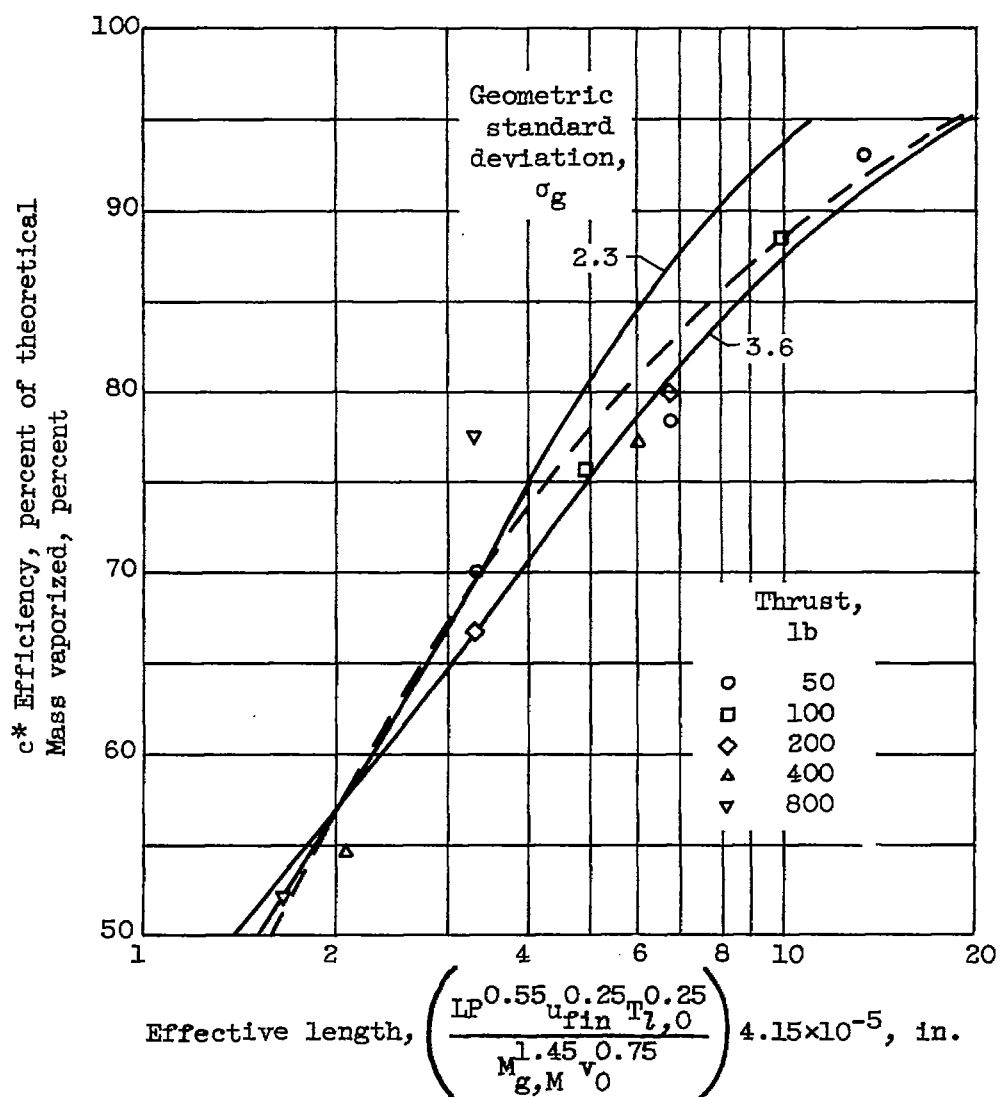Figure 5. - Concluded. Effect of fuel-orifice diameter on performance.

(a) Parallel-sheet injector. Slope, 2.0.

Figure 6. - Effect of fuel-orifice diameter on chamber length for given
performance.

(b) Triplet injector. Slope, 1.5.

Figure 6. - Concluded. Effect of fuel-orifice diameter on chamber length for given
performance.

Effective length, $\left(\dfrac{LP^{0.55}u_{fin}^{0.25}T_{l,0}^{0.25}}{M_{g,M}^{1.45}v_{0}^{0.75}}\right)4.15\times10^{-5}$, in.

(a) Parallel-sheet injector. $M_{g,M} = 0.11\ D^{1.4}$.

Figure 7. - Comparison of experimental and analytical results.
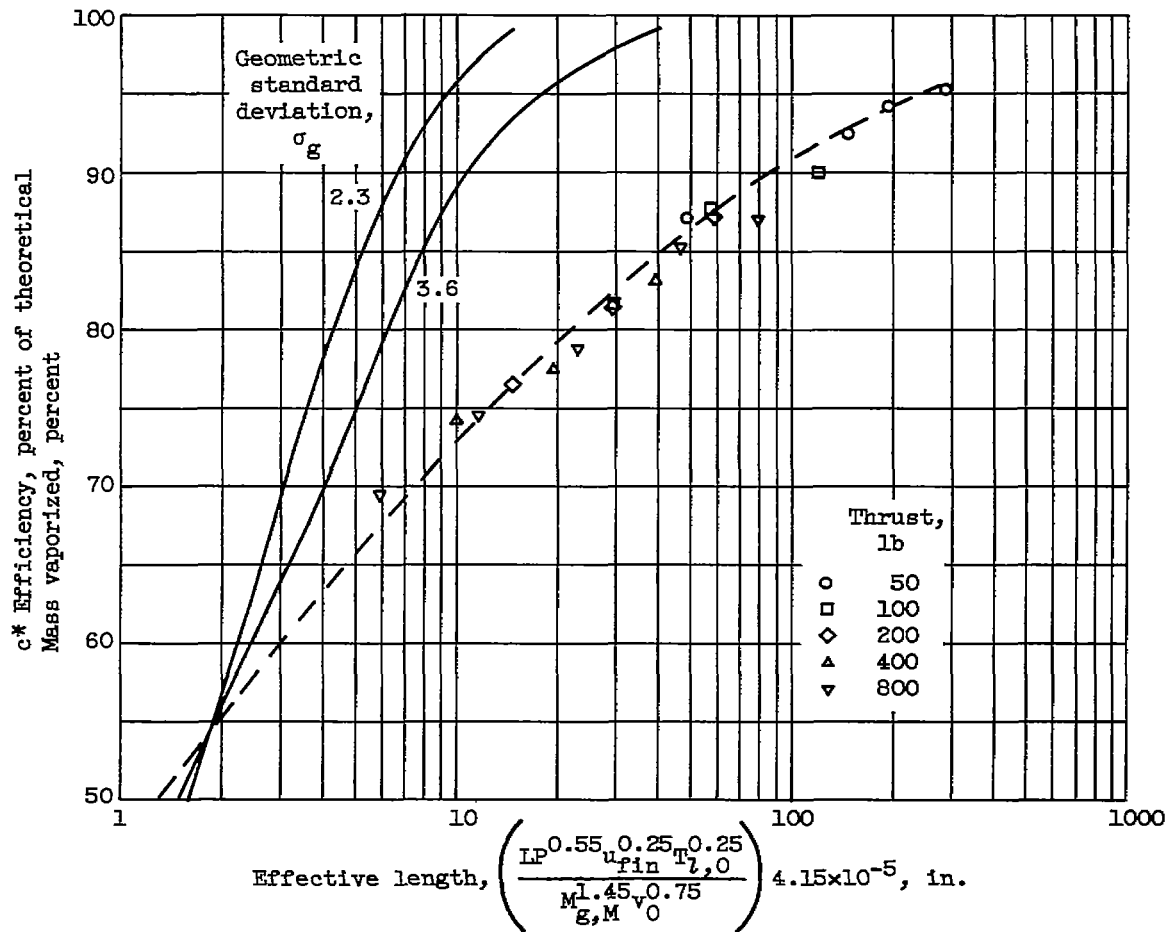
(b) Triplet injector. $M_{g,M} = 4.5 \times 10^{-3}$ D.

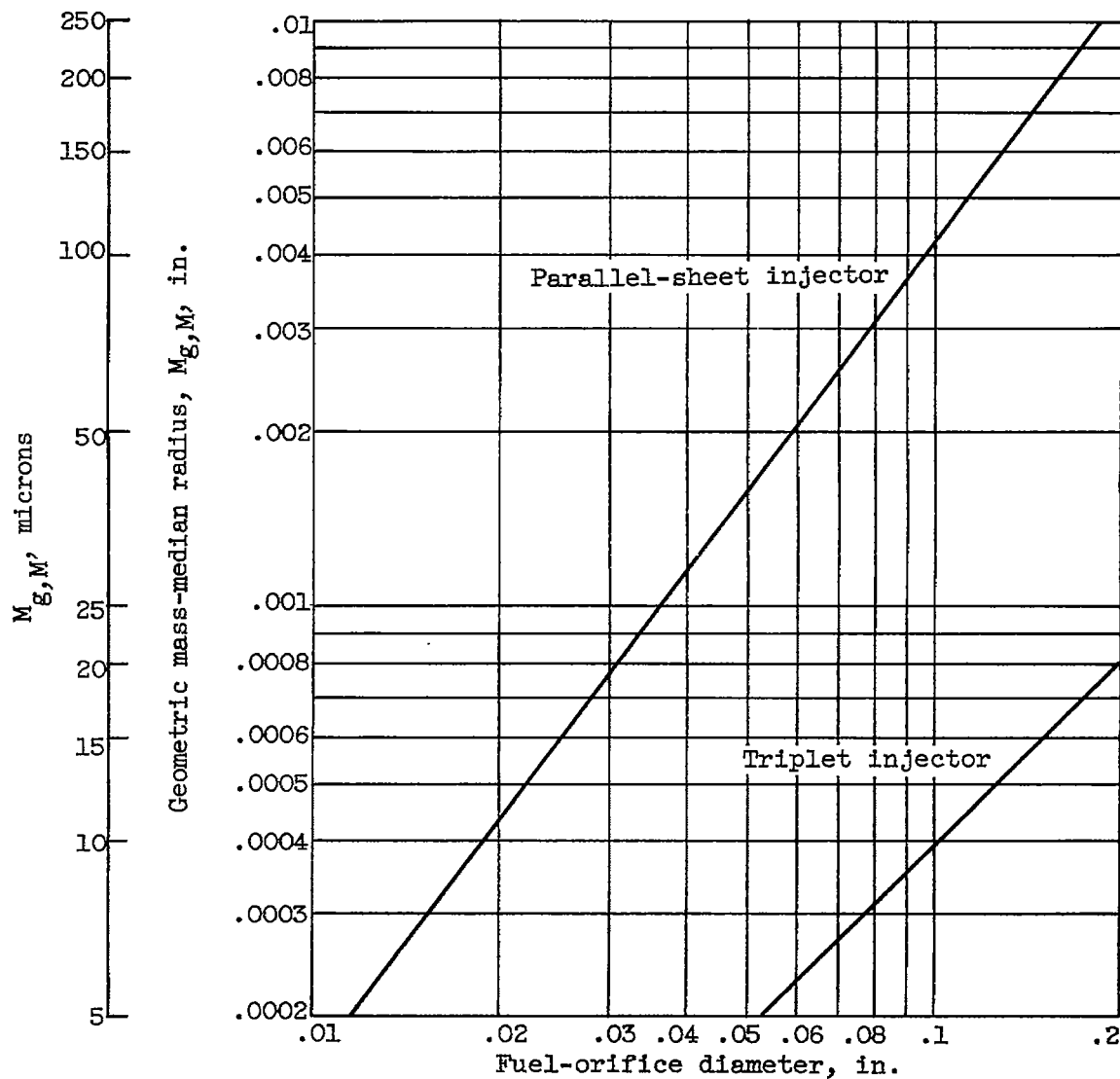Figure 7. - Concluded. Comparison of experimental and analytical results.

Figure 8. - Drop size.